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Microstructure of Friction Stir Welded 6061 Aluminum Alloy

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Abstract

The variation in the microstructure of a friction stir welded 6061 aluminum alloy was observed by a metallographic technique, electron backscatter diffraction pattern (EBSD), optical microscopy and transmission electron microscopy (TEM). At a low rotation speed and travel speed, the center portion of stir weld zone is dominated by a region deformed with a wedge-shaped microstructure, particularly in the lower branches. EBSD and TEM indicated that many more low-angle grain boundaries were observed in thermo-mechanically affected zone (TMAZ), i.e., subgrains with a recovered grain structure,. Friction heating and plastic flow during friction stir welding create fine recrystallized grains and recovered grains in the TMAZ. The friction stir welding produces a wedge-shaped portion and a softened region in the welded 6061 Al. In the stir zone, equiaxed grains were created and the grain size became very small in the bottom area.

1. Introduction

As the automotive industry moves towards an increased use of aluminum, the friction stir welding(FSW) process offers many potential benefits for joining aluminum. As FSW can produce high quality and low cost aluminum joints, it has been extensively studied. Recent studies report the textural gradients associated with FSW and dynamic recrystallization in pure Al 1100 [1-3], while they have suggested that the fine grain structure formed within the center of the weld zone is produced by dynamic recrystallization. The aerospace industry material 2024 Al alloy was also investigated for the evolution of its grain structure by electron back scatter diffraction (EBSD) [4]. The microstructures of the 5182 Al alloy before and after FSW were both examined [5]. Murr et al. presented a detail analysis of the precipitation and precipitation-related microstructures in friction stir welded 6061 aluminum utilizing conventional transmission electron microscopy[6,7]. Although the FSW process has had many developments in both tool designing and welding materials, there are still many uncertainities concerning the microstructure evolution that occurs during the welding process. The area surrounding the welding stir zone in the 6061 Al alloy, for example, the thermo-mechanically affected zone (TMAZ) or the boundary between the TMAZ and the welding stir zone, have not been fully investigated.

The purpose of this study is to investigate the grain and substructure formed during comparatively low rotation and travel speed friction stir welding of a 6061-T6 Al alloy. We tried to understand the microstructures and mechanical properties of these regions and clarify the dynamic flow mechanisms in TAMZ, especially at a low rotation speed.

2. Experimental Procedures

The material selected for this investigation was 6 mm thick 6061 Al alloy plates treated under the T6 condition. The chemical composition was as follows: Si 0.71, Fe 0.18, Cu 0.30, Mn 0.07, Mg 1.14, Cr 0.14, Zn 0.03, Ti 0.02, balance Al (all in mass%). The plates were held in compression and were rigidly clamped to the milling machine bed during welding. The diameters of the larger shoulder and small pin, which is threaded, were 20mm and 6 mm respectively. The same tool pins were used in every stirring process. The rotating tool was aligned flush along the contact line and parallel with the surface of the clamped metal plates. This created an integral joint by severe plastic deformation of the material affected by the passage of the stirring tool. In this report, the travel speed range was from 38 to 104 mm/min and the rotation speed range was from 530 to 1100 rpm.

After the welding stir process, specimens were cut into several sections perpendicular to the welding direction. Specimens were mechanically polished first with 1000 grit and 1500 grit SiC paper and then with 3 micrometer and 1 micrometer diamond paste. The final polishing of these specimens was accomplished using colloidal silica, after which they were then etched in a perchloric acid/methanol solution at 273 K. After these treatments, they were prepared for optical microscopic observation and EBSD measurement. The EBSD measurement was conducted using a JEOL SEM, selecting the conditions of 20 kV and a 15 mm work-distance.

The thin specimens for TEM were also sliced like the specimens for EBSD at about a 0.5 mm thickness, ground to about a 0.2 mm thickness and then thinned by electronic etching to about 0.1 mm. Disks 3 mm in diameter were punched from these thin slices. The TEM thin foils were produced by twin-jet polishing. The thin foils were examined using a JEOL JEM-2010 transmission electron microscope equipped with an energy dispersive X-ray spectrometer (EDS) detector.

3. Results and Discussion

Figure 1 shows several cross section images of a friction stir welded 6061 aluminum alloy plate for several different rotation speeds and travel speeds. Several features are prominent in the friction stir welded material. The center portion of the stir weld zone is dominated by a region deformed into a wedge-shaped microstructure, particularly in the lower branches, not in what is often referred to as the nugget zone. A small variation in the intercalation flow pattern is shown in this figure, suggesting that the pattern of the stir weld zone is associated with the tool rotation speed and travel speed effects on the extreme superplastic shear flow which is accommodated in the FSW process. These patterns in Figure 1 are also associated with the thread spacing in the steel screw tool. This is supported by comparing the screw tool with the image of the stir weld zone shown in Figure 2.

In Figure 2, a steel screw tool is overlaid on the cross section image of the stir weld zone. In the lower portion of the stir weld zone, the intervals of the intercalation wedge-shaped portion are equal to the intervals of the thread spacing. This suggests that the wedge-shaped microstructure on the weld center is produced by shear plastic flow arising from the rotation of the pin and is then affected by the non-homogeneous temperature distribution near the pin. The flow patterns of material similar to the patterns in this study have also been observed by Li et al. [8] in the longitudinal section of a friction stir weld of 2024 Al alloy / 6061 Al alloy.

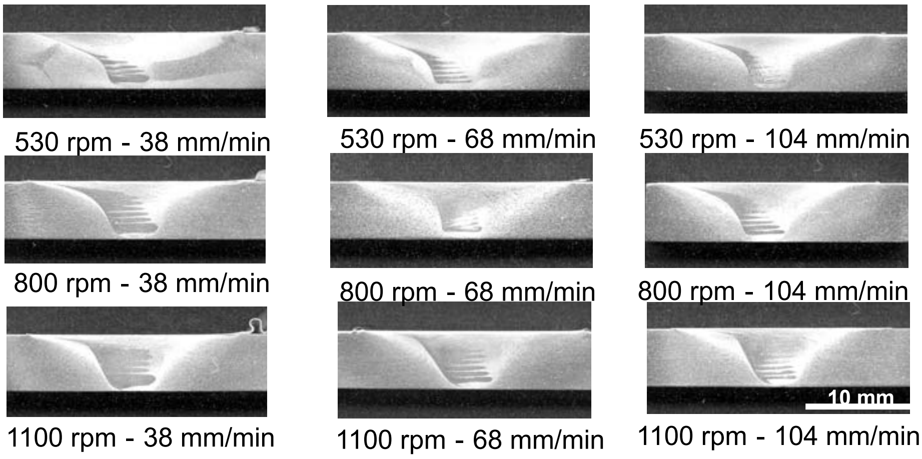

Figure 1: Cross sections of the defect free joints of 6061 Al Alloy at a rotation speed ranging from 530 to 1100 rpm and a travel speed ranging from 38 to 104 mm/min.

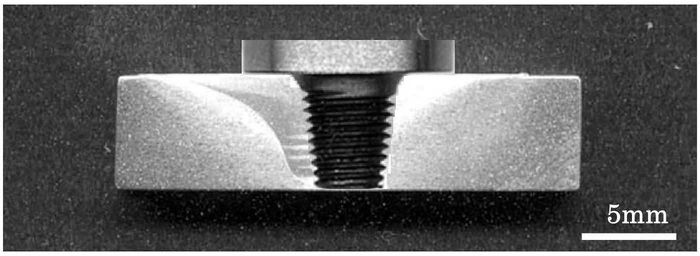

Figure 2: Image of processing of welded 6061 Al Alloy at a rotation speed of 1100rpm and a travel speed of 104 mm/min.

In order to further investigate the variation in the microstructure of the friction stir welded 6061 Al alloy, the specimens welded at an 800 rpm rotation speed and 38 mm/min travel speed were selected. Figure 3 illustrates a cross-section image of a typical friction stir weld of a 6061 aluminum alloy plate. The stir weld zone widens near the upper surface in contact with the rotation head-pin fixture, which is hereafter called the ‘shoulder region’. Next to the stir weld zone, affected by thermo and mechanical factor, the plastic flow pattern of the microstructure is identified in the optical micrograph and is called the thermo-mechanically affected zone (TMAZ). In the area next to the TMAZ, there is a region that is affected only by the welding heat and is usually called the heat-affected zone (HAZ).

Figure 4 shows micro-Vickers hardness profiles of the specimens produced at the same tool rotation speed as used in Figure 3. The hardness profiles were measured along the lines shown in Figure 3. The hardness data illustrate the uniformly general softening throughout the dynamically recrystallized weld zone and shows a very slight variance within the center of this zone and from the top to the bottom of the weld. Figure 4 also illustrates a variation in the hardness between the stir weld zone and the base (about 110Hv) hardness of roughly 60Hv.

Thus, the stir weld zone softening generally accounts for the hardness variance shown in Figure 3.

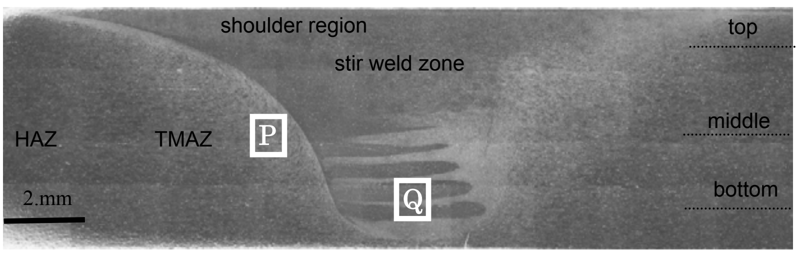

Figure 3: Cross-section of the optical overall micrograph in friction stir weld area, perpendicular to the tool traverse direction of the specimen produced at the tool rotation speed of 800 rpm and a traverse velocity of 38 mm/min.

In order to further investigate the variation in the microstructure of the friction stir welded 6061 Al alloy, the microstructures that are marked in region P shown in Figure 3 was observed by EBSP and TEM. Figure 5(a) shows a typical OIM map. High angle boundaries with misorientations of more than 15 degree are delineated by the thick black lines, while the low angle boundaries in the range from 4 degree to 15 degree by noted by the thin black lines. The grains that are delineated by the thick black lines tilt in one direction and were enlarged. It can be seen clearly that in the TMAZ, a strong flow plastic deformation occurred. By the point-to-point misorientation (θ) measurement along the line1 and the line

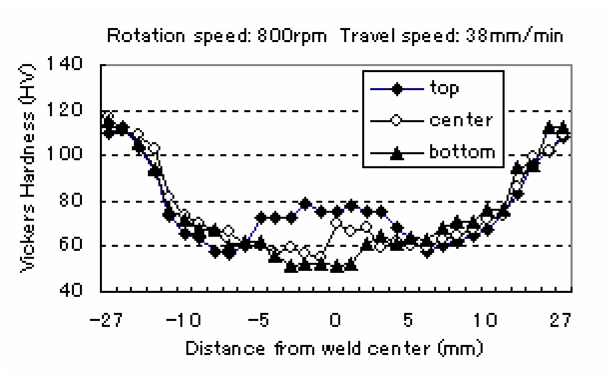

Figure 4: Micro-Vickers hardness through the transverse section in Figure 3 along the horizontal reference line shown by dotted line in Figure 3.

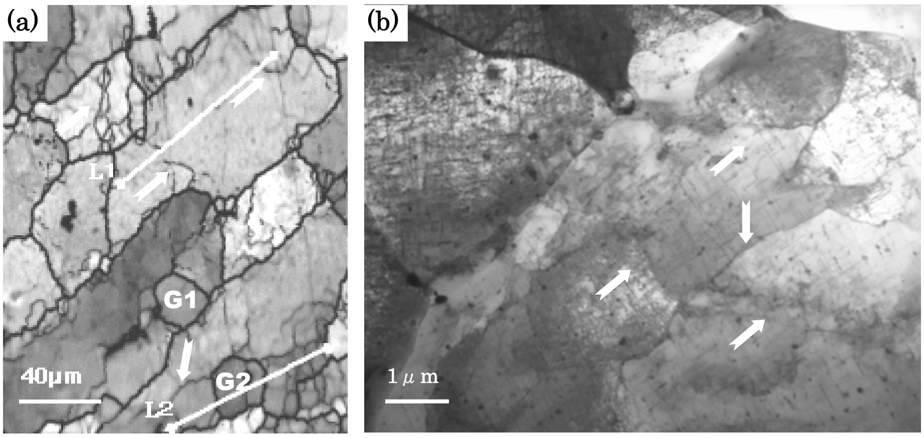

Figure 5: Microstructure in region P, (a) EBSP image (b) TEM image, the arrows show the subgrains.

L2, it can also be seen that a few fine grains have evolved along the corrugated grain boundaries, and new boundaries with a low angle misorientation have developed in some regions near the corrugated boundaries as indicated by narrows. These places may be the nucleation sites of new grains. In fact, some new grains have been formed, like grains G1 and G2. The fraction of low angle grains in this region increased to 0.4 and it is clearly seen that some subgrains and new fine grains were formed. This suggests mechanical effect in region P and that the grains rotate along an axis and then screw cut into fine grains. Base on these results, friction heating and plastic flow during the friction stir welding create fine recrystallized grains and recovered grains in the TMAZ. The TEM image of region P shows a subgrain structure in 5(b), as indicated by narrows. There is a low density of dislocations inside the subgrains.

Figure 6(a) shows the microstructure in region Q using optical microscopy. Fine recrystallized grains were created in this region. The hardness values of point H_D and H_L marked by the circles in Figure 3 were 50Hv and 66Hv, respectively, suggesting that the slight variance in the weld zone is associated with a homogeneous microstructure like that of the wedge-shaped microstructure. With a view to investigating the detailed microstructure of the light portion and dark potion, an EBSP measurement in the square region marked in 6(a) was carried out. Equiaxed grains were produced in this region.

The average grain size was 5.3 μ m. In the lower portion corresponding to the B region that is marked in 6(a), there is a band that has a grain size larger than the upper portion and it corresponds to the brighter wedge-shaped potion. This result corresponds to the result of the hardness at point H_D and point H_L, suggesting that the change in grain size affects the

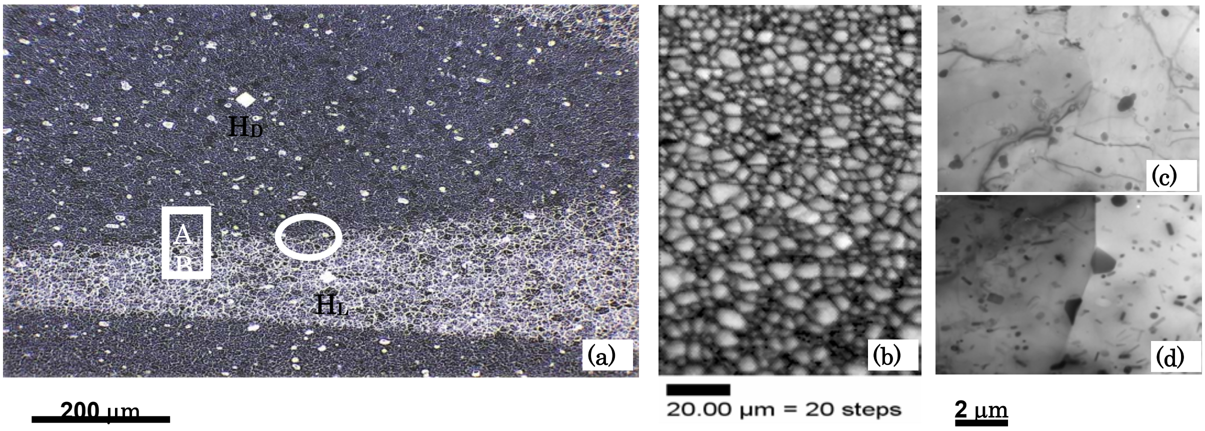

Figure 6: Microstructure of the stir zone (a) optical microscopy image in region Q. The hardness of dark(point H_D) and light(point H_L) microstructure is about 50 Hv and 66 Hv respectively. (b) EBSP image of square region, A: dark region; B: light region. (c) and (d) TEM image in ○portion.

hardness. Furthermore, the TEM examination in ○ portion was carried out. The lack of a precipitate area and a rich precipitate area exist in this portion. The lack of a precipitate area corresponds to dark region while the rich precipitate area corresponds to light region. This result suggests that the flow pattern is also affected by the existence of a precipitate. Mg-Si-Cu was found in (c) and Mg-Si and Si-O were found in (d) based on EDS measurements.

4. Conclusions

For a low rotation speed and travel speed, the center portion of the stir weld zone is dominated by a region deformed with a wedge-shaped microstructure, particularly in the lower branches, not in what is often referred to as the nugget zone. The forming of this flow pattern is significantly affected not only by the rotation speed and travel speed, but also by the existence of precipitates. In the TMAZ, severe plastic deformation appeared due to heat and mechanical effects and subgrains are formed for the large grains rotating along an axis due to the plastic grain flow. The equiaxied grains are formed in the center of the welded area by EBSD measurement.

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